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# Search for $B_s^0$ Oscillations in Semileptonic $B$ Decays

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This note describes a search for $B_s^0$ oscillations using semileptonic $B$ decays recorded by the CDF detector during Run II of the Fermilab Tevatron Collider on about 1 fb$^{-1}$ of data, *as it was in April 2006*. Opposite-side and same-side $b$ flavor taggers are used in this analysis. First we measure the $B^0$ oscillation frequency and calibrate opposite-side $b$ flavor taggers on a sample of semileptonic $B$ decays. A simultaneous analysis of $B^0$ and $B^+$ decays to $\ell D^0$, $\ell D^+$ and $\ell D^*$ final states has been performed. Beginning with tagger calibrations available from earlier analyses on the $\ell + SVT$ samples, we use the high statistic $\ell D$ sample to derive scale factors for predicted dilutions of the soft muon, soft electron and jet charge opposite-side taggers. Secondly we reconstruct $B_s^0 \rightarrow \ell^+ D_s^- X$ decays in three different $D_s^-$ channels, namely $\phi\pi^-$, $K^{*0}K^-$ and $\pi^+\pi^-\pi^-$. $D$ mass, lepton-$D$ mass and lifetime parameters for signal and backgrounds are determined with unbinned maximum likelihood fits. We validate our fitter and obtain sensitivity projections with toy Monte Carlo samples. The $\Delta m_s$ sensitivity on the semileptonic sample is 17.3 ps$^{-1}$. With the combination of the semileptonic and hadronic analyses we observe a signature consistent with $B_s^0 - \overline{B}_s^0$ oscillations. The probability that random tags background could fluctuate to mimic such a signature is 0.5%. Under the hypothesis that this is a signal for $B_s^0 - \overline{B}_s^0$ oscillations, we measure $\Delta m_s = 17.31^{+0.33}_{-0.18}$(stat.)$\pm$0.07(syst.) ps$^{-1}$.

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## I. INTRODUCTION

In the Standard Model, the $B_s^0$ meson exists in two $CP$-conjugate states, $|B_s^0\rangle = |\bar{b}s\rangle$ and $|\bar{B}_s^0\rangle = |b\bar{s}\rangle$. The two mass eigenstates of the $B_s^0$ meson, $B_s^H$ and $B_s^L$ ($H$ = 'heavy' and $L$ = 'light'), are not $CP$-eigenstates, but are mixtures of the two $CP$-conjugate quark states:

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle \text{ and } |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle, \quad \text{with } p^2 + q^2 = 1. \tag{1}$$

The mass and lifetime differences between the $B_s^H$ and $B_s^L$ can be defined as

$$\Delta m \equiv m_H - m_L, \quad \Delta\Gamma \equiv \Gamma_L - \Gamma_H \quad \text{and} \quad \Gamma = \frac{\Gamma_H + \Gamma_L}{2}, \tag{2}$$

where $m_{H,L}$ and $\Gamma_{H,L}$ denote the mass and decay width of $B_s^H$ and $B_s^L$. The probability $\mathcal{P}$ for a $B_s^0$ meson produced at time $t = 0$ to decay as $\bar{B}_s^0$ at proper time $t > 0$ is given by

$$\mathcal{P}_{B_s^0}^{\text{mix}} = \mathcal{P}(B_s^0 \to \bar{B}_s^0) = \frac{1}{2}\,\Gamma\, e^{-\Gamma t}\,[1 - \cos(\Delta m_s t)], \tag{3}$$

neglecting effects from $CP$ violation as well as a possible lifetime difference between the heavy and light mass eigenstates of the $B_s^0$. A measurement of the oscillation frequency $\Delta m_s$ gives a direct measurement of the mass difference between the two physical $B_s^0$ meson states.

Particle-antiparticle oscillations have been observed and well established in the $B^0$ system. The mass difference $\Delta m_d$ is measured to be $\Delta m_d = (0.505 \pm 0.005)$ ps$^{-1}$ [1]. However, observing the oscillation signal in the $B_s^0$ system has been challenging so far. The 95% C.L. limit for the mass difference is $\Delta m_s > 14.4$ ps$^{-1}$ [1]. In this analysis we search for $B_s^0$ flavor oscillations using semileptonic $B_s^0 \to \ell^+ D_s^- X$ decays and we study $B^0$ flavor oscillations using semileptonic $B \to \ell D X$ decays, recorded with the CDF detector during Run II of the Fermilab Tevatron Collider [2]. To measure time-dependent oscillations four ingredients are needed: 1) $b$ flavor at production time; 2) $b$ flavor at decay time; 3) proper decay time; and 4) large $B_s^0$ samples with good signal-to-background ratio.

We have developed an unbinned likelihood fitting framework based on mass, lepton-$D$ mass, proper decay length and tagging information of the reconstructed events. We apply opposite-side and same-side tagger algorithms to the data, using the expected dilution for each event. The $\ell D^0, \ell D^-, \ell D^*$ data samples are fitted simultaneously to determine the mixing frequency $\Delta m_d$ and the dilution scale factors of the opposite-side taggers. Dilution scale factors are introduced in the likelihood to compensate for differences between a perfect calibrated sample and the real $\ell D$ sample used in this analysis. Throughout this document references to a specific charge state imply the charge-conjugate state as well.

We have performed a similar analysis last October [3], but with 355 pb$^{-1}$ and using opposite-side taggers only. Several improvements compared to the previous analysis have been introduced. A very important new feature of the analysis is the inclusion of the same-side kaon tagger in addition to the opposite-side taggers. The invariant mass of the lepton and the $D$ meson is on average significantly lower for background events than for real $B$ signal events. A cut on this variable was applied to greatly reduce the background. As further step we have included the lepton-$D$ mass as a new variable on the unbinned likelihood framework. We have also used a finer binning on the $k$-factor distribution as a function of the lepton-$D$ mass. In addition we have increased the data sample by using more triggers, and moving to the whole data sample available.

## II. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of $\sim 1$ fb$^{-1}$, collected by the CDF II Detector between March 2002 and January 2006. The data is gathered with the so-called "Two-Track Trigger" and "lepton+$SVT$ Trigger". The first one selects events that contain track pairs with transverse momentum larger than 2 GeV/c and 120 $\mu$m $< d_0 <$ 1 mm, with $d_0$ the impact parameter of a track. These tracks are referred to as "SVT tracks". The second trigger requires one lepton with transverse momentum greater than 4 GeV/c plus and additional SVT track. Several semileptonic $B \to \ell DX$ meson decay modes are considered in the analysis, where the $D$ meson is reconstructed using the following decay modes: $D_s^- \to \phi\pi^-(\phi \to K^+K^-)$, $D_s^- \to K^{*0}K^-(K^* \to K^+\pi^-)$, $D_s^- \to \pi^+\pi^-\pi^-$, $D^{*-} \to \bar{D}^0\pi_*^-$ $(\bar{D}^0 \to K^+\pi^-)$, $D^- \to K^+\pi^-\pi^-$ and $\bar{D}^0 \to K^+\pi^-$.

The overall number of signal events and signal-to-background ratio for all channels are shown in Tab. II, where $S$ and $B$ are the number of candidate signal and background events. The $D$ and lepton-$D$ mass distributions are shown in Figs. 1 and 2 respectively. This analysis uses six $\ell D$ samples, but there are actually multiple decay paths that contribute to a given observed final state. Details on the selection, the sample composition and backgrounds coming from $B \to DX$ decays are given in [4].

| Decay | $S/B$ | $S$ |
|---|---|---|
| $\mu D^0$ | 3.8 | 409,600 $\pm$ 970 |
| $\mu D^+$ | 1.3 | 218,500 $\pm$ 940 |
| $\mu D^*$ | $\geq$ 50 | 53,900 $\pm$ 230 |
| $\mu D_s(\phi\pi^-)$ | 2.1 | 24,100 $\pm$ 240 |
| $\mu D_s(K^{*0}K^-)$ | 0.4 | 8,000 $\pm$ 160 |
| $\mu D_s(\pi^+\pi^-\pi^-)$ | 0.2 | 7,500 $\pm$ 210 |
| $eD^0$ | 3.7 | 142,300 $\pm$ 540 |
| $eD^+$ | 1.3 | 79,500 $\pm$ 630 |
| $eD^*$ | $\geq$ 50 | 21,000 $\pm$ 150 |
| $eD_s(\phi\pi^-)$ | 2.1 | 8,200 $\pm$ 130 |
| $eD_s(K^{*0}K^-)$ | 0.4 | 2,900 $\pm$ 90 |
| $eD_s(\pi^+\pi^-\pi^-)$ | 0.2 | 2,600 $\pm$ 130 |

TABLE I: Number of signal events and signal-to-background ratio for all combined $\ell D$ samples, where muons and electrons are given separately. Here background refers to combinatorial background only. A $3\sigma$ region around the $D$ mass peak was chosen to determine those parameters.

## III. DECAY LENGTH RECONSTRUCTION AND $ct^*$ EFFICIENCY

The transverse decay length $L_{xy}(B)$ is defined as the displacement $\vec{X}$ in the transverse plane from the primary event vertex to the reconstructed $B$ decay point, projected onto the $\ell D$ transverse momentum

$$L_{xy}^B = \frac{\vec{X} \cdot \vec{p_T}(\ell D)}{|\vec{p_T}(\ell D)|}. \tag{4}$$

The $B$ meson decay time is then given by

$$c\,t\,(B) = L_{xy}^B \frac{m(B)}{p_T(B)}, \tag{5}$$

where $m(B)$ is the $B$ mass [1]. Since we do not fully reconstruct the $B$ meson, we calculate the pseudo proper decay time $t^*$ of the reconstructed $B$ meson from the measured decay length $L_{xy}^B$ as

$$c\,t^* = L_{xy}^B \frac{m(B)}{p_T(\ell D)} \tag{6}$$

and introduce a correction factor

$$K = \frac{p_T(\ell D)}{p_T(B)}. \tag{7}$$

This $k$-factor corrects between the reconstructed $p_T(\ell D)$ and the unknown $p_T$(B) in the data. The $k$-factor distribution $\mathcal{F}(K)$ is obtained from a MC simulation of the signal semileptonic decays taking into account the sample composition.

Due to the SVT track $d_0$ requirement in the trigger and some additional cuts, the reconstructed proper decay time distribution $ct^*$ does not follow a pure exponential (modulo resolution and $k$-factor effects), but it is biased. This bias, expressed as an efficiency curve is obtained using Monte Carlo simulation. The $ct^*$ bias curve is parameterized with a functional form that is allows analytical integration in the likelihood fit method. The overall $ct^*$ distributions are shown in Fig. 3.

## IV. FLAVOR TAGGING

One of the components of measuring neutral $B$ mesons flavor oscillations is identifying whether the $B$ meson was produced as a $B$, which contains $\bar{b}$ antiquark, or a $\overline{B}$, which contains $b$ quark. We refer to this $B$ hadron flavor identification as "$b$ flavor tagging". The methods of $b$ flavor tagging may be classified into two categories: opposite-side taggers and same-side taggers. Opposite-side taggers exploit the fact that $b$ quarks in hadron colliders are mostly produced in $b\bar{b}$ pairs. Same-side flavor tags are based on the charge of particles produced in association with the production of the $B$ hadron. The performance of the $b$ flavor tags may be quantified conveniently by their efficiency $\epsilon$ and their dilution $D$. Efficiency is the fraction of $B$ hadrons on which the flavor tag can be applied, while dilution is related to the probability $\mathcal{P}$ that the tag is correct: $\mathcal{D} = 2\mathcal{P}$ - 1. This analysis uses so far three types of opposite-side taggers: soft muon [5], soft electron [6] and jet charge [7] taggers. The opposite-side taggers are applied exclusively. The one with the highest average dilution is applied first. The one with the next highest dilution is only applied on the so far untagged events. The use of the same-side kaon tagger offers the possibility of combining both taggers. Details on the opposite-side and same-side taggers are given in Ref. [4].

The performance of an opposite-side tagger is independent of the selected $B$ meson, hence it can be calibrated using the large $B^0/B^+$ data samples, before applying it in the $B_s^0$ sample. In addition we perform at the same time a measurement of $\Delta m_d$. In the case of the same-side kaon tagger [8], because the performance depends on the $B$ hadron, we need to rely on Monte Carlo simulation to obtain the expected behavior on $B_s^0$ mesons. The agreement between the data and the Monte Carlo for the $B^+$ and $B^0$ modes provides a powerful crosscheck of the simulation. We additionally assess systematic uncertainties in our ability to accurately model all different aspects of the data. When applying the same-side kaon tagger to different subsample, we account for the fact that the tagger performance varies with the average transverse momentum of the $B_s^0$ mesons in each sample.

## V. ANALYSIS OF $B_d$ OSCILLATION AND CALIBRATION OF OPPOSITE-SIDE TAGGERS

Reconstruction of time-dependent $B$ flavor asymmetry in the sample is necessary for any oscillation study. The probability density function describing the proper decay time of unmixed and mixed $B^0$ mesons is $(1 \pm \cos(\Delta m_d t)) \cdot e^{-ct/c\tau}$ where +(-) corresponds to the unmixed(mixed) meson. In order to determine whether a $B$ meson has mixed or not, its flavor at production and at decay time have to be determined. While the flavor at decay time can be inferred directly from the decay products (e.g. the lepton charge) the production flavor has to be deduced from other information in the event via flavor tagging methods. As said above, the reliability of a tagging method is typically characterized by the dilution $\mathcal{D}$. Due to uncertainty in flavor tagging the observed probability density function description of the $ct$ of the neutral $B$ candidates tagged as "mixed" or "unmixed" becomes $(1 \pm \mathcal{D}\cos(\Delta m_d t)) \cdot e^{-ct/c\tau}$. The dilution $\mathcal{D}$ used in the probability density function is built on event-by-event basis. This means that instead of using an average dilution for each tagger the dilution of the tagger is determined separately for each event, as e.g. a function of the $p_T^{rel}$ of the tagging lepton, the magnitude of the component of the opposite-side lepton momentum perpendicular to the axis of the jet which the lepton is associated to, or other quantities used for calibrating the tagger. As those dilutions have been calibrated on the inclusive lepton+SVT sample, the dilution for the $\ell D$ sample might be different. A dilution scale factor $S_{\mathcal{D}}$ for each tagger is introduced, hence the form of the signal $ct$ probability density function becomes $(1 \pm S_{\mathcal{D}}\mathcal{D}\cos(\Delta m_d t)) \cdot e^{-ct/c\tau}$. As we use event-by-event dilutions we add as well a term describing the probability density function of the predicted dilution for signal and background in the likelihood.

The evaluation of the systematic uncertainties was one of the main issues in this part of the analysis. The largest systematic uncertainty comes from the fake lepton background description and from the sample composition of the signal sample.

The following results are obtained for the $B_d$ oscillation frequency

$$\Delta m_d = 0.509 \pm 0.010 \text{ (stat.)} \pm 0.016 \text{ (syst.) ps}^{-1},$$

and for the overall tagging performance

$$\epsilon\mathcal{D}^2 = 1.54 \pm 0.04 \text{ (stat.)} \pm 0.05 \text{ (syst.) } \%.$$

The fit projections for the fitted asymmetries for each tagger in the combined $\ell D$ sample on 355 pb$^{-1}$ are shown in Fig. 4.

## VI. AMPLITUDE SCAN AND $\Delta m_s$ MEASUREMENT

For $\Delta m_s$ analyses, the amplitude method [9] is used to set limits on $\Delta m_s$ and combine results from different experiments when no oscillation signal is observed. An amplitude $\mathcal{A}$ is introduced in the expressions describing the mixed probability. The amplitude method works as follows: A $B_s^0$ oscillation amplitude $\mathcal{A}$ and its error $\sigma_{\mathcal{A}}$ are extracted as a function of a fixed test value of $\Delta m_s$ using a likelihood method. To a very good approximation, the statistical uncertainty on $\mathcal{A}$ is Gaussian and equal to the inverse of the significance $1/\mathcal{S}$. The statistical significance $\mathcal{S}$ of a $B_s^0$ oscillation signal can be approximated as [9]

$$\mathcal{S} \sim \sqrt{\frac{\varepsilon\mathcal{D}^2}{2}} \frac{S}{\sqrt{S+B}} \, e^{-(\Delta m_s \, \sigma_t)^2/2}. \tag{8}$$

If $\Delta m_s$ equals its true value $\Delta m_s^{\text{true}}$, the amplitude method expects $\mathcal{A} = 1$ within the total uncertainty $\sigma_{\mathcal{A}}$. If $\Delta m_s$ is tested far away from its true value, a measurement consistent with $\mathcal{A} = 0$ is expected. A value of $\Delta m_s$ can be excluded at 95% C.L. if $\mathcal{A} + 1.645\,\sigma_{\mathcal{A}} \leq 1$. If the true $B_s^0$ oscillation frequency $\Delta m_s^{\text{true}}$ is very large, far above the experimental sensitivity, $\mathcal{A} = 0$ is expected to be measured and all values of $\Delta m_s$ such that $1.645\,\sigma_{\mathcal{A}}(\Delta m_s) < 1$ are expected to be excluded at 95% C.L. Because of proper time resolution, the quantity $\sigma_{\mathcal{A}}(\Delta m_s)$ is an increasing function of $\Delta m_s$. It is therefore expected that individual values of $\Delta m_s$ can be excluded up to $\Delta m_s^{\text{sens}}$, where $\Delta m_s^{\text{sens}}$ is called the sensitivity of the analysis defined by $1.645\,\sigma_{\mathcal{A}}(\Delta m_s^{\text{sens}}) = 1$.

The discussion in Ref. [9] details a prescription for setting a limit on $\Delta m_s$ within an amplitude scan. The systematic uncertainty which is to be added to the statistical error on the amplitude is

$$\sigma_{\mathcal{A}}^{\text{sys}} = \Delta\mathcal{A} + (1 - \mathcal{A})\frac{\Delta\sigma_{\mathcal{A}}}{\sigma_{\mathcal{A}}}. \tag{9}$$

Here $\Delta\mathcal{A}$ is the difference in amplitude between the mean value of amplitudes of the default fit and the one with the systematic evaluation performed while $\Delta\sigma_{\mathcal{A}}$ is the corresponding difference in errors on both amplitude values. $\mathcal{A}$ and $\sigma_{\mathcal{A}}$ are the amplitude value and its error from the default fit.

In this analysis, large ensembles of Toy Monte Carlo experiments are used to evaluate the systematic uncertainty on the amplitude scan at several $\Delta m_s$ points. Two sets of samples of Toy MC samples are used. In one Toy MC experiment all of the defaults are set, and in the other set, the systematic effect under consideration is varied. An amplitude scan is then performed for each set of Toy MC samples and the resulting systematic uncertainty is defined by the mean of the errors according to Eq. (9). This procedure results in systematic uncertainties as a function of the $\Delta m_s$ value, $\sigma_{\mathcal{A}}^{\text{sys}}(\Delta m_s)$. The systematic uncertainties are then combined by adding them in quadrature for a given $\Delta m_s$ value. The combined systematic uncertainty is then folded into the exclusion limit by requiring

$$\mathcal{A} + 1.645\sqrt{\sigma_{\mathcal{A}}(\Delta m_s)^2 + \sigma_{\mathcal{A}}^{\text{sys}}(\Delta m_s)^2} \, < \, 1. \tag{10}$$

The dependence of the various systematic uncertainties as a function of $\Delta m_s$ is shown in Fig. 5. Overall, the systematic uncertainties are small compared to the statistical errors on the obtained amplitude fit values.

Using the data from the three $B_s^0 \to \ell^+ D_s^- X$ samples ($D_s^- \to \phi\pi^-$, $K^{*0}K^-$ and $\pi^+\pi^-\pi^-$), we perform an amplitude scan by repeating the likelihood fit for the amplitude $A$ for different values of $\Delta m_s$. In the default fit configuration, the amplitude $\mathcal{A}$ is the only free fit parameter.

The result of the combined amplitude scan on $\sim 1$ fb$^{-1}$ is shown in Fig. 6. The black dots represent the fitted amplitude with their respective statistical errors for each value of $\Delta m_s$. The yellow region indicates $1.645\sigma_A$ using statistical errors only while the green band includes combined statistical and systematic errors. The measurement is dominated by statistical uncertainties. Note, neighboring points are statistically correlated. From this distribution, a lower limit on the $B_s^0$ mixing frequency of $\Delta m_s > 15.9$ ps$^{-1}$ is derived at the 95% confidence level with a sensitivity of 17.3 ps$^{-1}$.

The combined sensitivity for the hadronic and semileptonic modes is 25.3 ps$^{-1}$, and the limit we set for the full analysis is $\Delta m_s > 16.7$ ps$^{-1}$ at the 95% confidence level [4]. The combined amplitude scan for hadronic and semileptonic modes is shown in Fig. 7.

The 95% confidence level is significantly lower than the expected limit because the amplitude shows a value consistent with unity near $\Delta m_s = 17.25$ ps$^{-1}$. To assess the significance of this deviation, we look at the ratio of the likelihood function at $\mathcal{A}$=0 and $\mathcal{A}$=1, as shown in Fig. 8. The maximum likelihood ratio is at $\Delta m_s = 17.33$ ps$^{-1}$ and has a value of 6.06. The probability that random tags background could fluctuate to mimic such a signature is 0.5%. More details are given in [4]. Under the hypothesis that this is a signal for $B_s^0 - \overline{B}_s^0$ oscillations, we measure $\Delta m_s = 17.31^{+0.33}_{-0.18}$(stat.)$\pm$0.07(syst.) ps$^{-1}$. The systematic error of this measurement is completely dominated by the *ct* scale uncertainty, which is of the order of 0.4%.

## VII. SUMMARY

In this analysis, we search for $B_s^0$ flavor oscillations using semileptonic decays recorded with the CDF detector during Run II of the Fermilab Tevatron Collider. Opposite-side and same-side tags provide information about the $B_s^0$ production flavor. Using an amplitude scan method, we obtain a 95% confidence level limit on the oscillation frequency $\Delta m_s > 16.7$ ps$^{-1}$ for a $\Delta m_s$ sensitivity of 25.5 ps$^{-1}$ using all combined hadronic and semileptonic modes. We observe a statistical significant signature consistent with $B_s^0 - \overline{B}_s^0$ oscillations, being the probability that random tags background could fluctuate to mimic such a signature 0.5%. Assuming this is a signal for $B_s^0 - \overline{B}_s^0$ oscillations, we measure $\Delta m_s = 17.31^{+0.33}_{-0.18}$(stat.)$\pm$0.07(syst.) ps$^{-1}$.

This analysis was published in PRL in Summer 2006 [10]. Furthermore, an improved analysis was published in December 2006 [11], which was the definive observation of $B_s^0 - \overline{B}_s^0$ oscillations.

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[2] D. Acosta *et al.* [CDF Collaboration], Phys Rev D 71, 032001 (2005) and references therein.
[3] *Study of $B_s \to \ell D_s X$ Oscillations in the Two-Track Trigger Sample*,
Publicly available through CDF's *B* Physics webpage at `http://www-cdf.fnal.gov/physics/new/bottom/bottom.html`
[4] *Measurement of $B_s^0 - \bar{B}_s^0$ Oscillation Frequency*,
Publicly available through CDF's *B* Physics webpage at `http://www-cdf.fnal.gov/physics/new/bottom/bottom.html`
[5] *Likelihood Based Soft Muon Tagging*,
Publicly available through CDF's *B* Physics webpage at `http://www-cdf.fnal.gov/physics/new/bottom/bottom.html`
[6] *Likelihood Based Soft Electron Tagging*,
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[7] *Improved Jet Charge Tagging in the Semileptonic Sample*,
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[8] *Same Side Kaon Tagging Studies in Fully Reconstructed Decays*,
Publicly available through CDF's $B$ Physics webpage at `http://www-cdf.fnal.gov/physics/new/bottom/bottom.html`

[9] H.G. Moser, A. Roussarie, *Mathematical methods for $B^0\bar{B}^0$ oscillations analysed"*, NIM A384(1997), 491-505.

[10] A. Abulencia *et al.* [CDF Collaboration], Phys.Rev.Lett. 97 (2006) 062003.

[11] D. Abulencia *et al.* [CDF Collaboration], Phys.Rev.Lett. 97 (2006) 242003.


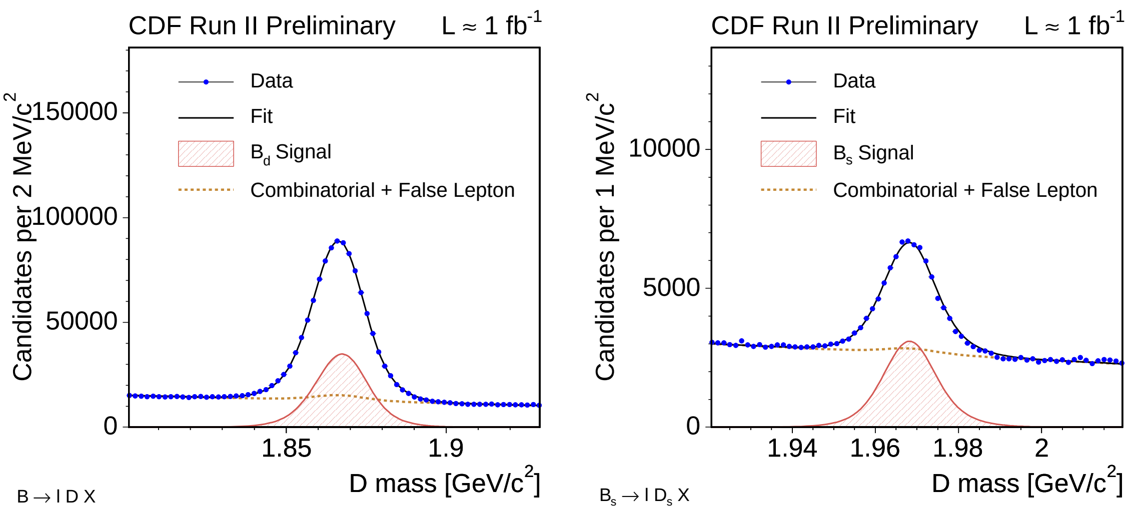


FIG. 1: $D$ meson mass distributions for $\ell D$ (left) and $\ell D_s$ (right) candidates in the combined 1 fb$^{-1}$ data sample.

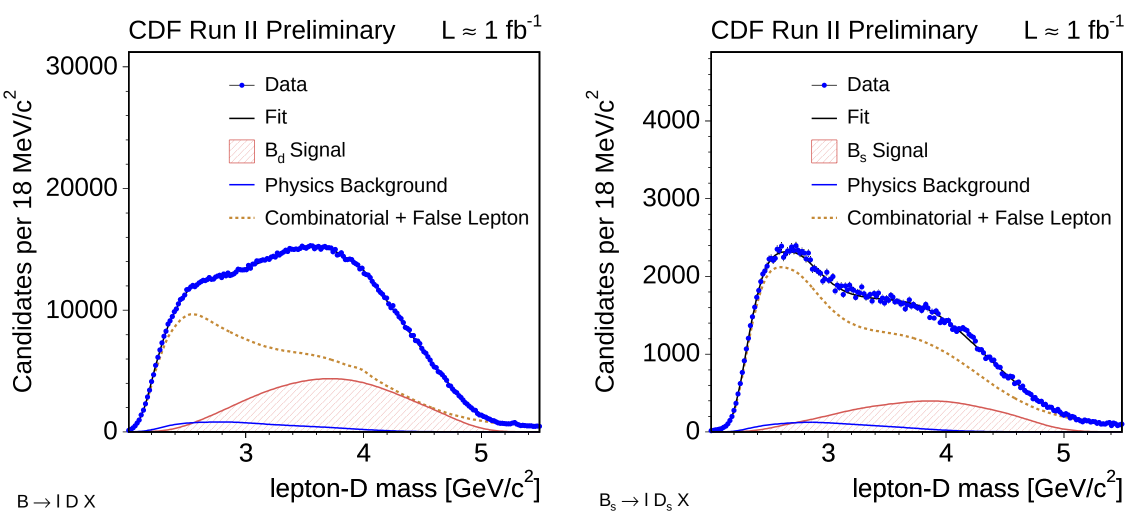


FIG. 2: Lepton-$D$ mass distributions for $\ell D$ (left) and $\ell D_s$ (right) candidates in the combined 1 fb$^{-1}$ data sample.

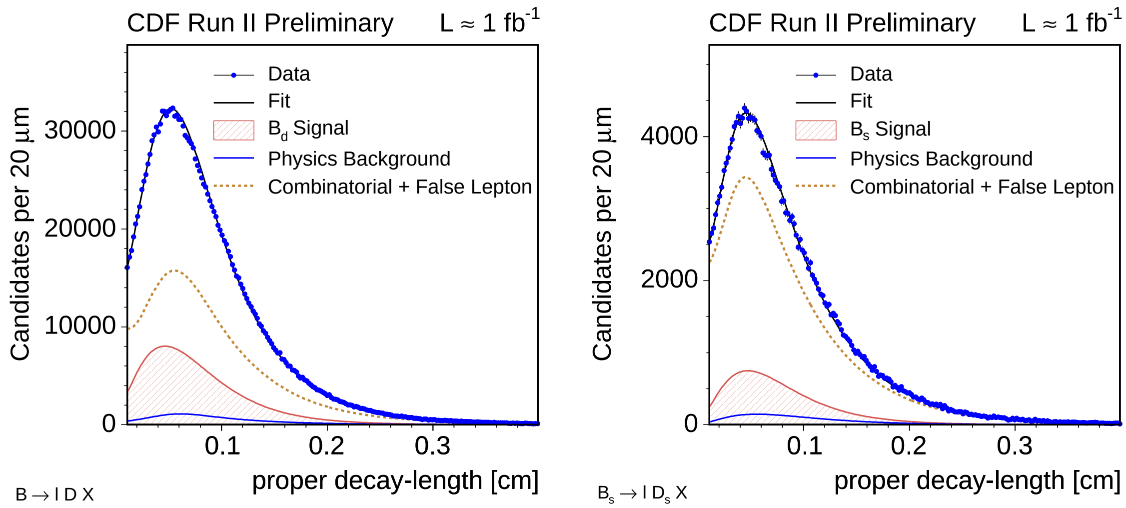


FIG. 3: $ct^*$ distributions for $\ell D$ (left) and $\ell D_s$ (right) candidates in the combined 1 fb$^{-1}$ data sample.

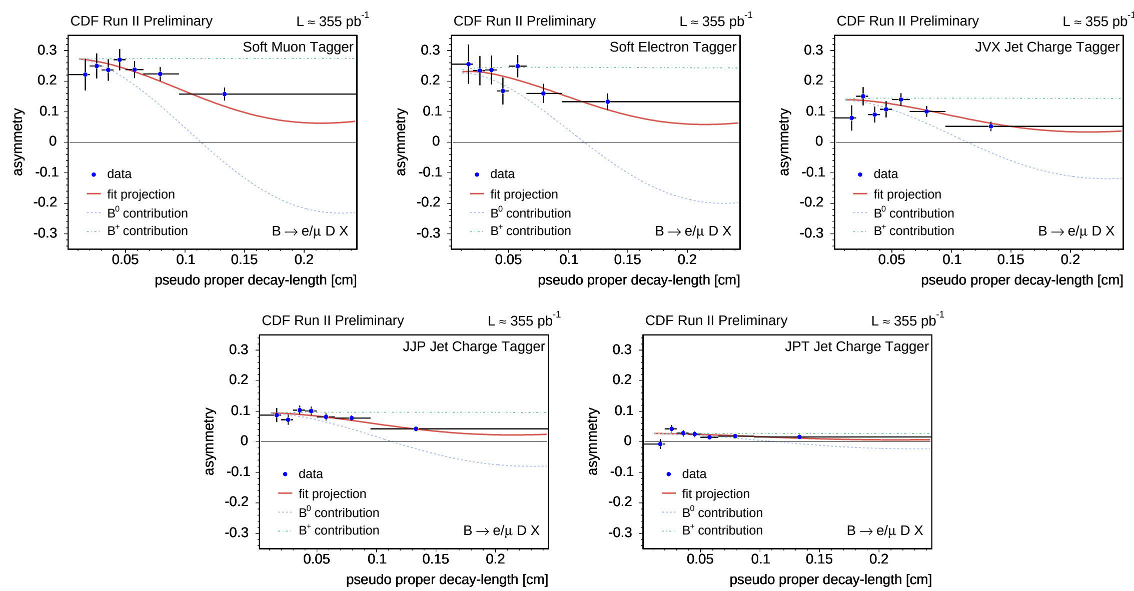


FIG. 4: Fit projections of the asymmetry in the combined $\ell D$ sample. From top to bottom and left to right: SET, SMT, JVX, JJP, JPT tagged candidates.

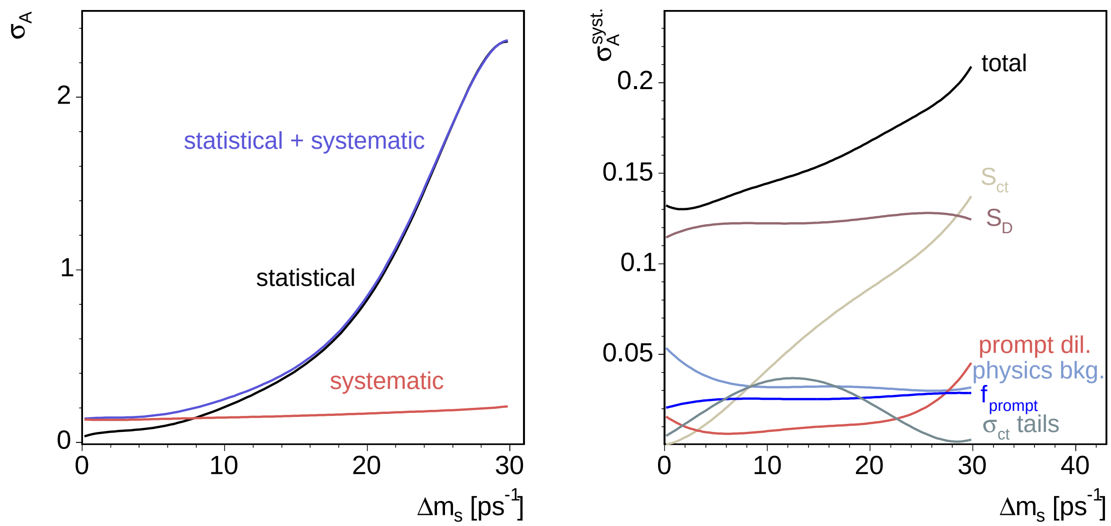


FIG. 5: Summary of various systematic uncertainties as a function of $\Delta m_s$ (left) and comparison between the statistical and systematic uncertainties as a function of $\Delta m_s$ (right).

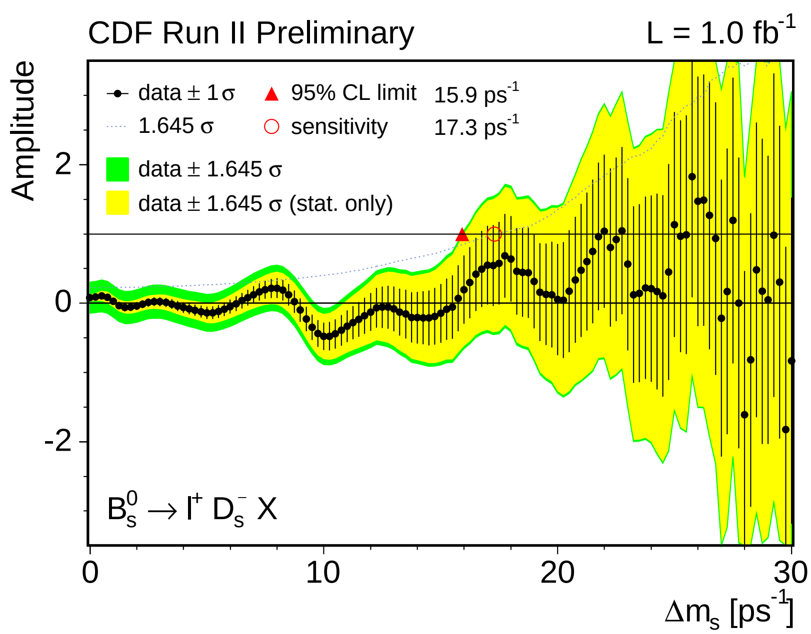


FIG. 6: Amplitude scan in data for all combined $B_s^0 \to \ell^+ D_s^- X$ decays. Statistical and systematic errors are considered.

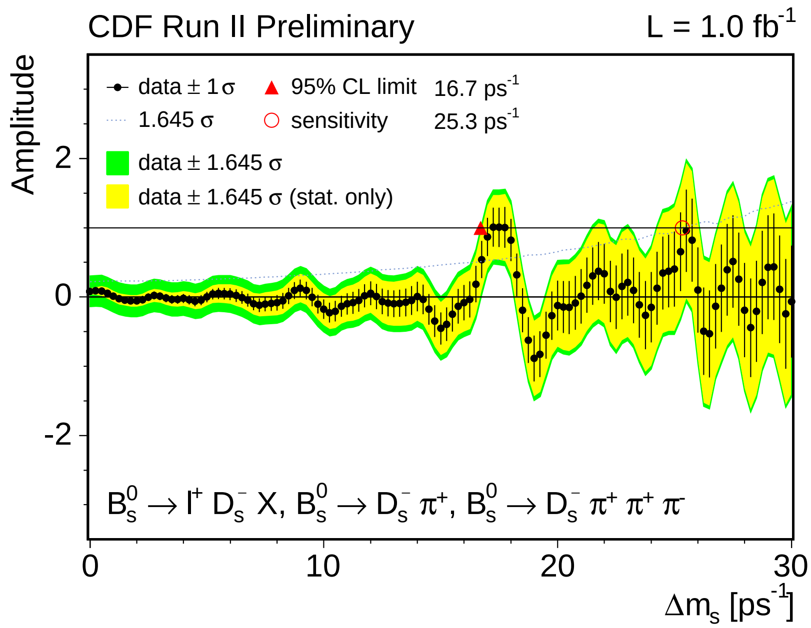


FIG. 7: Combined amplitude scan for hadronic and semileptonic modes.

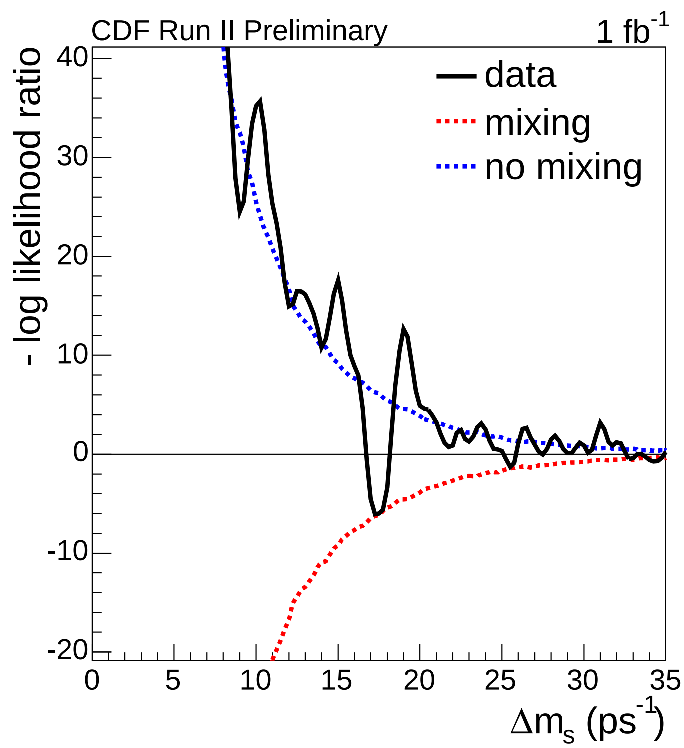


FIG. 8: Combined likelihood ratio as a function of $\Delta m_s$.